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A Study on Topographical Properties and Surface Wettability of Monolithic Zirconia after Use of Diverse Polishing Instruments with Different Surface Coatings

Al-Haj Husain, Nadin ; Özcan, Mutlu

Abstract: PURPOSE To investigate the surface topography parameters and wettability of monolithic zirconia (MZ) using polishing instruments with different coatings. MATERIALS AND METHODS MZ specimens (N = 50, n = 10 per group) (12 × 12 × 1.8 mm) were highly polished. Five polishing systems were studied: BG: silicon carbide polishers; CG: diamond-impregnated ceramic polisher kit; EV: synthetically bonded grinder interspersed with diamond; SL: urethane-coated paper with aluminum oxide grits; and DB: diamond bur (8 m). Specimens were initially roughened with 220 m grit diamond burs (10 seconds, 160,000 rpm). After baseline measurements, they were further polished for 10 seconds using a slow-speed handpiece under water coolant, except for SL using a custom-made device (7.5 N), with speed ranging between 5000 and 30,000 rpm. Topographical changes were evaluated considering (a) weight (digital scale), (b) volume loss (digital microscope), (c) vertical height loss (digital microscope), (d) surface roughness (Ra) (profilometer), and (e) surface wettability (goniometer, water). RESULTS Compared to baseline, material loss from the surface after polishing (ΔW) ranged between 0.00 ± 0.0001×10 and -0.03 ± 0.008×10 g (SL < CG < BG < DB < EV) and the volume loss (ΔV) between 900 ± 3×10 and 2459 ± 7×10 m (SL < BG < CG < DB < EV). The vertical height loss (VH) was highest for SL (-18.911 ± 3.5) and lowest for EV 55.19 ± 6.3 m (SL < BG < CG < DB < EV). The surface roughness (m) difference (Ra) was lowest for DB (-0.14 ± 0.02) and the highest for EV (0.86 ± 0.42) (DB < BG < SL < CG < EV). BG showed the lowest contact angle difference (SW) -2.79 ± 0.8° and EV the highest (3.93 ± 3.1°) (BG < DB < SL < CG < EV). CONCLUSIONS All polishing instruments performed similarly when Ra values were considered. SL, BG, and CG produced the least material loss. Synthetically bonded rubber bur interspersed with diamond (EV) could not be suggested for polishing MZ.

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A Study on Topographical Properties and Surface Wettability of Monolithic Zirconia After Use of Diverse Polishing Instruments with Different Surface Coatings

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Short title: *Surface profile change in zirconia after polishing*

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ABSTRACT

Objectives*:* Improper surface finishing of fixed dental prosthesis (FDP) made of monolithic zirconia (MZ) may cause opposing enamel wear. The objectives of this study were to investigate the surface topography parameters and wettability of MZ using polishing instruments with different coatings and sequences, simulating the clinical workflow.

Materials and Methods*:* MZ specimens (N=50, n=10 per group) (Katana Zirconia HT, Kuraray-Noritake) (12 mm x 12 mm x 1.8 mm) were obtained and highly polished. The specimens were randomly allocated to 5 groups depending on the polishing systems to be studied, namely BG: Silicon carbide polishers (Brownie, Greenie, Super Greenie, Shofu); CG: Diamond impregnated ceramic polisher kit (Ceragloss, Edenta); EV: Synthetically bonded grinder interspersed with diamond (EVE Kit, EVE); SL: Urethane coated paper with aluminium oxide grits (Soflex Finishing and Polishing System Kit, 3M ESPE) and DB: Diamond bur (8 μm, FG9205/6, Intensiv). Polished specimens were initially roughened with 220 μm grit diamond burs (Grinding Bur-GB, Intensiv) (10 s, 160,000 rpm) and considered for baseline measurements in order to detect the polishing efficacy. They were ultrasonically cleaned and further polished. Each step in all polishing systems was performed for 10 s using a slow-speed hand piece under water-cooling (50 ml/min) except for SL. Polishing was performed in a custom made device under 750 g load, with rpm ranging between 5000 to 30.000 depending on the manufacturer`s instructions. For DB a high-speed hand piece was used at 75.000 rpm. Topographical changes were evaluated considering a) Weight (Digital scale), b) Volume loss (Digital microscope), c) Vertical height loss (Digital Microscope), d) Surface roughness (Ra) (Profilometer) and e) Surface wettability (Goniometer, water).

Results*:* The amount of material loss from the surface after polishing compared to baseline (ΔW) ranged between $-3\pm0.1\times10^{-4}$ and $-296\pm8\times10^{-4}$ g in ascending order as follows: $SL^a<CG^a<BG^a<DB^b<EV^c$. The volume loss after polishing compared to baseline (ΔV) ranged between $-0.158\pm0.03\times10^{-6}$ and

$0.245 \pm 0.07 \times 10^{-6}$ mm^3 ($SL^{a}<BG^{a}<CG^{a,b}<DB^{b}<EV^{c}$). The vertical height loss after polishing compared to baseline (ΔVH) ranged between -18.91±3.52 and 55.19±6.26 µm ($SL^{a}<BG^{a}<CG^{a,b}<DB^{b}<EV^{c}$). The surface roughness difference after polishing compared to baseline (ΔRa) ranged between -0.143±0.015 and 0.855±0.419 µm ($DB^{a}<BG^{a}<SL^{a}<CG^{a}<EV^{b}$). The contact angle after polishing compared to baseline (ΔSW) was between -3.93±0.79° and 2.79±3.14° ($BG^{a}<DB^{a}<SL^{a}<CG^{a}<EV^{a}$).

Significance*:* All polishing instruments performed similar when ΔRa values are considered, indicating that monolithic zirconia could not be polished ideally with the tested polishing regimens. After 10 to 40 s of polishing, SL, BG and CG performed similar, producing the least material loss of the MZ tested. Synthetically bonded rubber bur interspersed with diamond (EV) could not be suggested for polishing monolithic zirconia.

Keywords: Monolithic zirconia; Polishing; Surface properties; Tribology; Y-TZP.

1. Introduction

The most commonly experienced clinical failures of fixed dental prosthesis (FDP) made of zirconium dioxide (hereafter: zirconia) framework veneered with glassy matrix ceramic systems is chipping or fractures of the veneering ceramic.[1] The cause of this failure type is multifactorial and has been the focus of research interest during the last years.[2] According to the available clinical trials, where different combinations of zirconia and veneering ceramics were studied, it appears that chipping or fracture of veneer ceramics could not be eliminated completely.[1]

Recently, as an alternative to such bilayered ceramic FDPs, monolithic zirconia systems have been introduced. Highly sintered monolithic zirconia offers superior stability but lower translucency as opposed to its all-ceramic counterparts (feldspathic-, glass- and glass-reinforced ceramics).[3] Yet, together with its low radioactivity [4], this material has favourable chemical, biological and mechanical properties.[5-8] Since monolithic zirconia does not necessitate the use of veneering ceramic, less tooth preparation is required and due to the lack of technical procedures needed for the veneering process, they currently present an economic alternative to veneered metal-ceramic or veneered zircona FDPs. Moreover, the absence of veneering ceramic eventually would not cause chipping and thus could be considered as a solution to chipping type of failures.

While chipping problem will be solved with the use of monolithic zirconia FDPs, another problem is being faced clinically, namely the wear of the tooth enamel opposing monolithic zirconia. There are two types of zirconia Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) milling processes: hard milling involves machining of densely sintered zirconia, whereas soft milling generates enlarged frameworks out of presintered zirconia.[3] Hard machining is often used for the fabrication of dental implants and implant abutments, and soft milling for the fabrication of crowns and multiple unit FDPs, followed by sintering at high temperature.[9] CAD/CAM milling process leaves inevitable grooves associated with the surface of the drill at a range of 60 - 300 µm depending on the CAD/CAM system.[10] Prior to cementation, dental technicians need to polish such grooves on the outer surface of the FDP. Unfortunately, removal of premature contacts after cementation as a result of cement film thickness clinically requires repolishing. Consequently, this may impair mechanical properties of the material but most importantly cause wear of the opposing enamel that could be considered an iatrogenic damage. Limited number of clinical studies indicated enamel wear of 10 µm and zirconia material of 33 µm within observation duration of only 6 months.[11]

Zirconia is an extremely hard material (1140 Knoop Value)[3] and considering also the clinical conditions, it is very difficult to repolish the material ideally to the level of baseline situation. Hardness of the material coupled with the rough topography and surface texture may later yield to opposing enamel wear. Polishing ceramic materials are known to decrease the surface roughness and thereby, less wear of opposing enamel.[12] In fact, polished zirconia was reported to cause even less wear of opposing enamel than the enamel opposing enamel.[13] Hence, ideal polishing systems and polishing protocols need urgent investigation that delivers the best surface properties for zirconia. Employing the best polishing protocol may eventually diminish opposing enamel wear and plaque accumulation that could also be a setback depending on the location of the rough surface on the FDP.[14]

Current polishing instruments available for ceramics are often advised to be used sequencially at various rotation per minute (rpm) from rough to fine, and are usually available as silicon carbide, diamond or aluminum oxide impregnated rubbers or burs. According to the results of some in vitro studies, smooth surfaces have been obtained by using rubber polishers coated with diamond abrasive particles or diamond polishing pastes.[15-17] Sof-Lex discs have also been described as an efficient polishing method for glassy matrix ceramics.[18,19] Unfortunately, all these studies employed only one polishing regimen within each study, where polishing of zirconia was accomplished manually and enamel antagonist material loss was measured after cyclic loading in a chewing simulator, at number of cycles ranging between 120,000 to

1,200,000 (Table 1).[20-26] Thus, the focus of these studies was not to test the efficacy of polishing instruments but to analyze the antagonist enamel wear opposing zirconia surfaces with and without glaze.

The objectives of this study therefore were to investigate the topographical properties such as volume loss, vertical height loss, surface roughness and wettability properties of monolithic zirconia with small grain size before and after various polishing regimens, simulating the clinical workflow and to propose the best polishing system that also causes less damage to the material. The null hypothesis tested was that the polishing systems based on different surface coating and impregnation technologies would not show significant difference on the surface topography parameters and wettability of monolithic zirconia.

2. Materials and methods

2.1 Specimen preparation

All experimental procedures are presented in Fig. 1.

Specimens (N=50, n=10 per group) were cut from small grain size (<0.5 μm) zirconia blocks (Katana Zirconia HT, Kuraray-Noritake, Aichi, Japan) (Chemical composition: ZrO_2, Y_2O_3; flexural strength: >900 MPa; fracture thoughness: 5 MPa√m) using an electrical precision diamond wire saw with blade diameter of 0.17 mm and 30 μm roughness under constant water cooling (Well, Walter Ebner, Locle, Switzerland).

The surfaces of the sectioned specimens were polished manually with 2400 μm grit silicon carbide paper (Streuers, Willich, Germany) under water-cooling until a flat surface was obtained. The thickness was verified with a digital micrometer (Mitutoyo, Kamagawa, Japan). The specimens were then sintered in a high-temperature furnace (Nabertherm LHT02L16, Nabertherm GmbH, Bremen, Germany) at 1500°C for 7 hours according to the manufacturer's instructions. Finally, specimens of 1200±20 μm x 1200±20 μm x 260±20 μm were obtained after sintering.

2.2 Initial polishing and grinding (baseline)

All specimens were initially finished with silicon carbide discs (Abramin, Struers, Ballerup, Denmark) of 25 μm for 2 min using a lubricant (Diluant, Presi, Leocole, Switzerland), followed by 15, 9, 6, 3 and 1 μm discs in sequence for 4 min each using a suspension (Diamond Spray Suspension, DP, Struess, Denmark) at 250 rpm.

A custom made device (The Dhriller™, University of Zurich, Switzerland, Designer: MÖ) (Figs. 2a-b) was constructed to achieve controlled grinding and polishing procedures that could operate under different rpm and pressure levels where high and slow speed handpieces (Intramatic Lux 700KL, KaVo Dental AG, Brugg, Germany) could be connected to the dental unit (KaVo ESTHETICA Comfort 1065, KaVo Dental AG). The device allowed controlled movement of the handpiece bidirectional horizontally at the given trace of movement in millimetres upon the specimen that is fixed in a metal holder. The device could allow the handpiece to apply constant load 120 to 750 g depending on the purpose. Throughout the finishing procedures, the grinding and polishing instruments were positioned parallel to the specimen surfaces.

The polished zirconia specimens were ground with 220 μm grit diamond rotatory burs with shoulder edge (Diameter: 0.13 mm, Length: 12 mm, FG 5410L/6, Intensiv, Montagnola, Switzerland) at 160.000 rpm using the high-speed hand-piece for 10 s. After the grinding procedures, the specimens were ultrasonically cleaned (Bransonic Ultrasonic Cleaner 3510, Branson, Danbury, USA) in isopropanol for 10 min.

2.3 Final polishing procedures

The ground zirconia specimens were randomly allocated to 5 groups depending on the polishing systems to be studied, namely BG: Silicon carbide polishers (Brownie, Greenie, Super Greenie, Shofu, Ratingen, Germany); CG: Diamond impregnated ceramic polisher kit (Ceragloss, Edenta, St. Gallen, Switzerland); EV: Synthetically bonded grinder interspersed with diamond (EVE Kit, EVE, Pforzheim, Germany); SL: urethane coated paper with aluminium oxide grits (Soflex Finishing and Polishing System Kit, 3M ESPE, St. Paul, MN, USA) and DB: Diamond bur (8 μm, FG9205/6, Intensiv) (Table 2, Figs. 3a-f).

Each step in all polishing systems was performed for 10 s using a slow-speed hand-piece under water-cooling (50 ml/min), except for SL (Table 3). Polishing was performed in a custom made device under 750 g load, with rpm ranging between 5000 to 30.000 depending on the manufacturer`s instructions. For DB, a high-speed hand piece was used at 75.000 rpm. The specimens were cleaned ultrasonically for 10 minutes in isopropanol after each step.

2.4 Measurement parameters and procedures

Topographical and material related changes were evaluated considering a) Weight loss (∆W), b) Volume loss (∆V), c) Vertical height loss (∆VH), d) Surface roughness (∆Ra) and e) Surface wettability (∆SW). For each parameter, measurements from the final polished specimens were subtracted from baseline measurements.

In order to calculate the ∆W, the weight of final polished specimen was subtracted from initially polished and ground specimen (baseline) using a digital scale (Adventurer Pro AV264C, Ohaus, Pine Brook, NJ USA).

For each specimen, ∆V and ∆VH were calculated by subtracting the scans of the final polished surfaces from baseline scans using a digital microscope (VHX-2000D, Keyence, Osaka, Japan). The scans were obtained from an area of 2.5 mm length and 2 mm width from a pre-established reference point situated in the middle of each specimen at x200.

The mean roughness parameter ∆Ra was measured from the same specimens using a contact profilometer (Profilometer, Perthometer S2, Mahr, Göttingen, Germany) and the corresponding software program (MarSurfXR 20, Mahr) at the following settings: traversing length: 2.4 mm; standard critical wavelength: 0.25 mm; velocity: 0.1 mm/s.

∆SW was calculated from contact angle measurements. One sessile drop of water was applied on the ceramic surface at 23°C room temperature. Three consecutive contact angle measurements were performed using a camera-based goniometer (Easydrop Drop Shape Analysis System, Kruess, Hamburg, Germany) using its corresponding software (Drop Shape Analysis Software for Windows, DSA Version 1.90.0.14). Water of 0.1-µl drop was placed on the specimen surface located on a movable table using a micro syringe (diameter: 1.1mm, NE42, Kruess). The drop was illuminated from one side and the camera from the opposite side captured the image of the drop, 10 seconds (30 frames per second). The image was then transferred to the computer and the contact angle was determined with the software referring to distilled water as the substance liquid [27]:

$\Delta p = \delta \, . \, (1 / r1 + 1 / r2)$

where

Δp is the difference in pressure between the outside of the drop and its inside.

r1 and r2 stand for the principle radii of the curvature.

All measurements were repeated 3 times for all parameters.

2.5 Microscopy evaluations

Digital images were made from zirconia specimen surfaces at baseline and after final polishing regimens (VHX-2000D) at x200 for visual inspection. Additionally, in order to observe the changes on the non-used and used burs and polishing instruments qualitatively, scanning electron microscopy (SEM) images were made. Instruments were initially mounted on aluminium stubs and gold/palladium sputter-coated for 10 nm (90 s, 45mA; Balzers SCD 030, Balzers, Liechtenstein). SEM images were obtained at 10 kV, x40 and x2000 magnification (Zeiss Supra V50, Carl Zeiss, Oberkochen, Germany). Furthermore, EDAX elemental analysis was performed on unused and the last bur of each polishing system (Evaporation: 10 nm carbonate at 0.1 nm/s, 1.78 Ve, 0.67 mA; first 6 nm at 45°, next 4 nm at 90°) (High Vacuum Coating System MED020, Leica, Brugg, Switzerland).

2.6 Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (version 18.0, SPSS Inc, Chicago, IL, USA). Data for each measurement parameter (5 levels: ΔW, ΔV, ΔVH, ΔRa, ΔSW) and polishing regimens (BG, CG, EV, SL, DB) were analyzed using one-way ANOVA, post hoc Scheffé and Wilcoxon tests. In addition, correlation coefficients between measured parameters were calculated using regression analysis with linear correlation. $P \leq 0.05$ was considered to be statistically significant in all tests.

2. Results

The amount of material loss from the surface after polishing compared to baseline (ΔW) ranged between $-3\pm0.1\times10^{-4}$ and $-296\pm8\times10^{-4}$ g in ascending order as follows: $SL^{a}<CG^{a}<BG^{a}<DB^{b}<EV^{c}$ (one-way ANOVA, Scheffé) (Table 4).

The volume loss after polishing compared to baseline (ΔV) ranged between $-0.158\pm0.03\times10^{-6}$ and $0.245\pm0.07\times10^{-6}$ mm^3 ($SL^{a}<BG^{a}<CG^{a,b}<DB^{b}<EV^{c}$) (Table 4).

The vertical height loss after polishing compared to baseline (ΔVH) ranged between -18.91 ± 3.52 and 55.19 ± 6.26 μm ($SL^{a}<BG^{a}<CG^{a,b}<DB^{b}<EV^{c}$) (Table 4).

The surface roughness difference after polishing compared to baseline (ΔRa) ranged between 0.143 ± 0.015 and 0.855 ± 0.419 μm ($DB^{a}<BG^{a}<SL^{a}<CG^{a}<EV^{b}$) (Table 4).

The contact angle after polishing compared to baseline (ΔSW) was between -3.93 ± 0.79 and $2.79\pm3.14°$ ($BG^{a}<DB^{a}<SL^{a}<CG^{a}<EV^{a}$) (Table 4).

Regardless of the polishing system, ΔW (Table 5) and ΔV (Table 6) decreased significantly compared to baseline measurements except for EV, where significantly higher ΔV values were obtained, indicating more material loss (Wilcoxon). After polishing compared to baseline measurements, ΔRa decreased significantly for BG but increased significantly for CG and EV. Similarly, significantly lower ΔSW was observed with EV (Table 5). After polishing compared to baseline measurements, ΔVH decreased significantly for the groups

BG, CG, while it increased significantly for EV (Table 6). ΔW and ΔV decreased significantly compared to baseline measurements except for EV, where significantly higher ΔV values were obtained, indicating more material loss. While a positive correlation coefficient of 0.526 was found between ΔW and ΔV, a negative correlation (-0.034) was noted between ΔRa and ΔVH (Table 7).

Digital images were made from zirconia specimen surfaces after final polishing regimens that showed more microscopical material loss in the form of defects and pores in the EV and deeper grooves in the CG group. All polishing systems did not completely eliminate the baseline grooves (Figs. 4a-f).

SEM images indicated more loss of diamond particles on the polishing instruments (CG, EV) but less from the diamond burs, yet being coated with zirconia smear (Figs. 5a-e, 6a-o, 7a-o, 8a-o, 9a-t, 10a-e). After use, BG demonstrated some fiber exposure accompanied with loss of silicon carbide from the surface. As for SL, loss of urethane coating and detachment of large aluminium oxide grits from the disks were evident with the coarse ones but with the fine ones, again the disc surfaces seemed to be coated with zirconia smear.

The EDAX analysis showed Zirconia atomic percentages for the used burs ranging from 0.01 to 0.66: EV (0.01) < SL (0.06) < BG (0.07) < CG (0.21) < GB, DB (0.66). The wt % of Zirconia for the used burs ranged from 0.08 to 3.81: EV (0.08) < SL (0.36) < BG (0.41) < CG (0.81) < DB (3.65) < GB (3.81) (Figs. 11a-f).

3. Discussion

This study was undertaken to investigate the changes in surface topography features and material properties of small grain size monolithic zirconia after various polishing regimens, and to identify the best polishing system that causes less damage to the material. Based on the results of this study, since polishing systems studied showed significant differences in all studied parameters except for surface wettability, the null hypothesis could be partially rejected. From methodological point of view, zirconia specimens were initially highly polished and subsequently roughened again so that subtracting the final measurements from the baseline situation could deliver information on polishing efficacy of the instruments. Also, no glaze was applied on the zirconia surfaces to eliminate the possible effects of porous glaze ceramic. Similarly, the use of slurry such as diamond polishing pastes was not considered in this study that may further cause two body wear of the polishing surface and the slurry and affect the ranking of the performance of the polishing systems.

A variety of polishing instruments were explored in this study having different coatings. Each polishing system included sequential polishing regimens starting from course to fine instruments, also operating at different rpm, which yielded to 1 to 4 steps of polishing. Each consecutive step was applied only 10 seconds that added to a total of minimum 10 to maximum 40 s of polishing duration depending on the polishing system. The results indicated that compared to baseline situation (initial polishing and roughening), in terms of material weight loss (ΔW), volume loss (ΔV) and vertical height loss (ΔVH) after 30 to 40 s of polishing, SL, BG and CG did not show significant difference that eventually produced the least material loss of the monolithic zirconia tested.

Pathological wear of enamel opposing full-coverage zirconia FDPs cannot be generalized at this moment due to the limited clinical information but early results show alarming amounts of enamel loss.[11] However, according to results of in vitro studies, polished zirconia specimens show favourable wear behaviour of opposing natural teeth. Some studies comparing different zirconia ceramic systems observed more enamel wear opposing glazed specimens,[22,23,25] whereas in another study, no difference between glazed and polished specimens was observed.[21] The reason for this was attributed to the fact that glaze was removed during the wear process due to the contact damage as a result of two body wear. Thus, the underlying zirconia surface that was not polished then accelerated wear of enamel upon glaze removal. Nevertheless, studies observed that even when the zirconia surface under the glaze layer was polished with abrasive paper, the glazed specimens presented more antagonist wear than the polished specimens.[21,23] Roughness of ceramic restorations affects the wear behaviour negatively if not polished well, while it contributes to minimizing the wear of ceramic and its natural antagonist if reduced by polishing.[21,22,23,25] Limited information is available on the efficiency of different surface polishing systems on zirconia.[26] Therefore, the results of this study were compared to one experiment performed on glass ceramic,[20] glass infiltrated alumina[24] and one on translucent and shaded zirconia with the diamond abrasive kit (BruxZir set).[26]

Ra of all the specimens in this study increased slightly up to 0.29 μm after grinding. This increase was also reported for the translucent and shaded zirconia (Ra up to 1.15 μm),[24] the values differ because of differing experimental conditions, especially due to the higher pressure used during the grinding procedure at the current study. Preliminary tests where 125 g force was applied, could not detect measurable results for material loss or roughness. Thus, the load was increased to 750 g indicating that higher forces should be practiced during polishing zirconia due to hardness of this material. High-pressure values seem to result in smoother surfaces but more weight loss compared to low-pressure application. Also, during the preliminary studies, it was noted that measurements x500 magnification at the digital microscope might miss information regarding the roughness of the surface, in that only smooth parts of the grooves at the peaks or valleys may be captured that does not represent the overall roughness. Accordingly, measurements were made at x200 magnification.

All polishing instruments performed similar when ΔRa values are considered. This indicates that zirconia could not be polished ideally at the durations tested. Depending on the ceramic material and the polishing systems used, glass infiltrated alumina and leucite glass ceramic materials showed Ra values ranging from 0.2 μm to 0.7 μm after polishing with EV, SL and BG polishing systems. For lithium disilicate ceramic (IPS Empress CAD), SL presented significantly lower Ra values than the control glazed group, while EV and BG showed significantly higher values. For leucite glass ceramic (Vita Mark II), SL achieved significantly lower Ra than the glazed group, while there was no statistical significance between the glazed group and EV or

BG [28]. In the present study, the mean Ra values ranged from 0.13 μm to 1.11 μm where the groups DB and BG demonstrated lower values, and CG and EV resulted in higher values than SL (0.28 μm), yet not significant. Within the groups significance between the grinded and the last polishing step considering Ra were observed for the groups CG, BG and EV. As for CG and EV, the values of the polished specimens were significantly higher and influenced the surface smoothness negatively. The reason for this could be explained on the grounds that the first polishing step of both systems roughened the surface, while the second one smoothed it, the third step of CG influenced the Ra minimum, not reaching a lower value than the grinding value. In contrast, the third step of EV roughened the surface even further. A possible explanation is that with longer polishing times some grains of the material itself could disengage resulting in surface damage and higher roughness values. Therefore, reducing the EV method to a two-step polishing system by omitting the first instrument could be considered less harmful to the material, which requires further investigations. The Ra values of BG polished specimens were significantly lower than those of the other groups, as the first step of the BG system smoothed the surface the most, while the last two steps did not seem to present further effect. A similar trend was observed in another study.[24] In the DB group, the mean Ra values decreased after polishing as well but it was not significant.

As for the SL system, the first step increased the Ra value, the second one decreased it, while the third one increased it again and the fourth led to a slight decrease. The polish with the smoothest surface was achieved with the SL medium treatment and fine or superfine discs did not further decrease the Ra value. This phenomenon was also observed in a study where glass ceramic was used as a substrate.[20] In that study, loss of abrasive particles were noted on the fine and superfine discs after 30 s of polishing time. Deprived of particles, the discs seem to damage the ceramic surface revealing slight scratches and plastic smear marks.[20] Digital microscope images in this study did not reveal plastic smear on the zirconia specimens probably because of the ultrasonic cleaning after polishing. These results are in accordance with those of an in vitro study that analysed ceramic surfaces with a profilometer obtaining 0.2 μm as mean Ra value for SL. The same study used also BG, revealing rougher surfaces compared to SL. The reason for this could be associated with the lower pressure and inadequate adaptation of the polishing instrument on the specimen surface as information was not available regarding the applied force and as to whether polishing was performed free hand or not. Although according to the results of another study, BG presented the lowest mean Ra value with a statistically significant difference in comparison with CG and SL.[26] Digital microscope images of EV and CG confirm high surface roughness values.

Although DB and BG expressed lower Ra values than SL, considering the lower material loss measured as weight and volume loss, SL could be considered as the best polishing method for flat monoclinic zirconia. Yet, larger surface area of the SL discs may cause roughness and material loss other than the areas being targeted for polishing on the FDP surface. For the removal of premature contacts from the FDP surface, essentially polishing instruments with pointed tips should be considered. Since no significant difference was found between BG and SL, pointed shaped BG that requires also less steps could be more efficient as it reduces the chairside time and at the same time delivers similar surface properties. Additional investigations are needed on tooth shaped FDPs. Furthermore, certain steps of some polishing methods do not contribute to improved smoothness and could be omitted in order to accelerate the workflow. Among all polishing systems, synthetically bonded grinder interspersed with diamond, EV, resulted in the highest material loss and created more roughness. The use of this instrument should be practiced with caution for polishing zirconia.

Wear of a material may also influence contact geometry that may eventually affect bacterial plaque adhesion especially in less cleansable areas of an FDP.[28] As for the wettability, contact angle values were similar with all polishing systems indicating that surface roughness did not influence this parameter.

Apparently, surface energy was not influenced by the polishing regimens. Future studies should also look at bacterial adhesion on the same rough areas of zirconia.

One other interest of this study was to verify the reliability of the volume loss and vertical height loss measurements obtained in the digital microscope with the weight and Ra values. The positive but weak correlation (r=0.5) between ΔW and ΔV indicates that digital microscope could be used as an acceptable device for measuring material loss related parameters. Contact profilometer may also further damage the surface depending on the surface hardness of the substrate material. In that respect, non-contact profilometers could be more appropriate in measurement of such parameters. However, the negative correlation between ΔRa and ΔVH indicates the necessity of improvement in scanning features of the microscope.

The toughness of zirconia ceramic is related to its capacity for tolerating damage and is mostly related to phase transformation, where the tetragonal (t) phase is transformed into the monoclinical (m) phase. In this transformation, the energy absorbed by the zirconia matrix in the vicinity of the propagating crack is consumed by the t grains to transform into a m symmetry, which is accompanied by ~ 3-4% volume expansion. This volume expansion hinders crack propagation by means of compressive stress.[29,30] Thus, in order to maintain this beneficial feature of zirconia ceramic, the phase transformation should be avoided at any rate to avoid crack propagation. The phase transformation in zirconia accompanied with the progressive nucleation of m phase has been previously demonstrated to have a strengthening effect short term for the compressive stress accumulated on the surface layer.[9,31] However, the progress of the transformation leads to grain pullout and surface degradation, by the applied stresses, leading eventually to the failure of the FDP enhanced by the aqueous environment. Surface grinding has been suggested to create a region of compressive stresses on the zirconia surface, which increased its mean flexural strength.[32,33] Hand grinding, when compared to machine grinding, was more effective at inducing the t → m phase transformation, thus increasing the strength of zirconia.[34] Hand ground surface contained almost five times more m than severely machined ground surface of the same material.[34] This was attributed to the extensive heat generated during severe machine grinding in spite of a stream of coolant that was directed near the cutting edge during grinding. Consequently, locally developed temperatures exceeded the temperature for m → t transformation, thus the reverse m → t transformation occurred. In contrast, the t → m transformation was retained upon hand grinding at lower speed and grinding force, which was not associated with extensive heat generation. Instead, due to high stresses developed during grinding, severe surface cracks must have been formed which decreased the strength and reliability of the material. In another study, Xu et al.[35] reported an improvement in the strength of zirconia upon fine grinding with a 25 µm diamond wheel, whereas coarser grinding resulted in strength reduction. Similarly, Kosmac et al.[29] advocated fine grinding as a finishing procedure to improve the mean strength and reliability of milled zirconia. On the other hand, in a recent study[36], fine diamond grinding significantly decreased the flexural strength of zirconia in spite of the compressive stress created. Considering the flexural strength results, lower Weibull modulus, the higher amount of m phase and rougher surface, mechanical surface modification of zirconia with fine diamond burs were not recommended in clinical procedures. Studying tribological changes on material surfaces, in this case polishing, is a difficult task as parameters of duration, pressure, abrasiveness of the polishing instruments, operating conditions such as rpm according to manufacturers recommendations and sequence, hardness of the materials to be polished involved. All these parameters need to be considered simultaneously when suggesting the most efficient polishing system on any material. Moreover, clinically finishing and polishing is a free hand procedure, which was standardized using a kind of robotic device in this study. Thus, from clinical perspectives, suggesting the sweet spot involves more pressure application in the sequential use of the corresponding polishing instruments with the shortest duration of 10 s per instrument. It has to be noted that in this study, the specimens were ultrasonically cleaned between polishing procedures that is not possible in clinical conditions. Thus, the apparent zirconia smear on polishing instruments or vice versa may be inevitable in clinical conditions. SEM EDAX analysis showed Zirconia smear on every bur and polisher used with the GB and DB having the most. EV showed the least amounts of zirconia smear that could be attributed to to the high amount of material loss from the polisher itself.

The choice of monolithic zirconia as an FDP material as opposed to veneered zirconia will certainly eliminate the chipping problem. The question remains whether removing the premature contact using burs from monolithic zirconia FDP surface and subsequently prolonged duration and sequence of polishing instruments would impair mechanical strength of the material or not.

5. Conclusions

From this study, the following could be concluded:

1. Compared to baseline situation (initial polishing and roughening), in terms of material weight loss (ΔW), volume loss (ΔV) and vertical height loss (ΔVH) after 10 to 40 s of polishing depending on the system, SL, BG and CG performed similar, producing the least material loss of the monolithic zirconia tested.

<u>2. All polishing instruments performed statistically similar ΔRa values but BG delivered the smoothest surfaces.</u>

3. Synthetically bonded grinder interspersed with diamond, EV, yielded to the highest material loss and created more roughness, thus could not be indicated for polishing zirconia.

4. Contact angle values were similar with all polishing systems.

5. The positive correlation between ΔW and ΔV implies digital microscope is an acceptable tool for measuring these parameters but the negative correlation between ΔRa and ΔVH indicates the need for improvement in scanning properties of the microscope used.

6. Wear of antagonist enamel and material loss during polishing of monolithic zirconia are serious clinical concerns and limited information is available to date. Yet, among all polishing instruments tested, BG could be advised causing the least damage and providing the best surface properties of zirconia.

REFERENCES

1. Raigrodski AJ, Hillstead MB, Meng GK, et al: Survival and complications of zirconia-based fixed dental prostheses: a systematic review. J Prosthet Dent 2012;107:170-7.

2. Al-Amleh B, Lyons K, Swain M: Clinical trials in zirconia: a systematic review. J Oral Rehabil 2010;37:641-52.

3. Kelly JR, Denry I: Stabilized zirconia as a structural material. Dent Mater 2008;24:289-98.

4. Manicone PF, Rossi Iommetti P, Raffaelli L: An overview of zirconia ceramics: basic properties and clinical applications. J Dent 2007;35:819-26.

5. Christel PS: Zirconia: The second generation of ceramics for total hip replacement. Bull Hospital Joint Dis Orthopaedic Institute 1989;49:170-7.

6. Guazzato M, Albakry M, Ringer SP, et al: Strength, fracture toughness and microstructure of a selection of all ceramic materials. Part I: pressable and alumina glass-infiltrated ceramics. Dent Mater 2004;20:441-8.

7. Guazzato M, Albakry M, Ringer SP, et al: Strength, fracture toughness and microstructure of a selection of all ceramic materials. Part II. Zirconia based dental ceramics. Dent Mater 2004;20:449-56.

8. Tinschert J, Natt G, Mohrbotter N, et al: Lifetime of alumina- and zirconia ceramics used for crown and bridge restorations. J Biomed Mater Res Part B, Appl Biomater 2007;80:317-21.

9. Piconi C, Maccauro G: Zirconia as a ceramic biomaterial. Biomaterials 1999;20:1-25.

10. Estagan D, Dussetschleger F, Agosta C et al: Scanning electron microscope evaluation of CEREC II and CEREC III inlays. Gen Dent 2003;515:450-4.

11. Stober T, Bermejo JL, Rammelsberg P et al: Enamel wear caused by monolithic zirconia crowns after 6 months of clinical use. J Oral Rehabil 2014;41:314-22.

12. Elmaria A, Goldstein G, Vijayaraghavan T et al: An evaluation of wear when enamel is opposed by various ceramic materials and gold. J Prosthet Dent 2006;96:345-53.

13. Olivera AB, Matson E, Marques MM: The effect of glazed and polished ceramics on human enamel wear. Int J Prosthodont 2006;19:547-8.

14. Passos SP, Torrealba Y, Major P et al: In vitro wear behavior of zirconia opposing enamel: A systematic review. J Prosthodont 2014;23:593-601.

15. Scurria MS, Powers JM: Surface roughness of two polished ceramic materials. J Prosthet Dent 1994;71;174-7.

16. Jung M: Finishing and polishing of a hybrid composite and a heat-pressed glass ceramic. Oper Dent 2002;27;175-183.

17. Bottino MC, Valandro LF, Kantorski KZ et al: Polishing methods of an alumina-reinforced feldspar ceramic. Braz Dent J 2006;17;285-9.

18. Martínez-Gomis J, Bizar J, Anglada JM et al: Comparative evaluation of four finishing systems on one ceramic surface. Int J Prosthodont 2003;16;74-7.

19. Glavina D, Skrinjaric I, Mahovic S et al: Surface quality of Cerec CAD/CAM ceramic veneers treated with four different polishing systems. Eur J Paediat Dent 2004;5;30-4.

20. Flury S, Lussi A, Zimmerli B: Performance of different polishing techniques for direct CAD/CAM ceramic restorations. Oper Dent 2010;35;470-81.

21. Jung YS, Lee JW, Choi YJ et al: A study on the in-vitro wear of the natural tooth structure by opposing zirconia or dental porcelain. J Adv Prosthodont 2010;2:111-115.

22. Mitov G, Heintze SD, Walz S et al: Wear behavior of dental Y-TZP ceramic against natural enamel after different finishing procedures. Dent Mater 2012;28:909-18.

23. Janyavula S, Lawson N, Cakir D et al: The wear of polished and glazed zirconia against enamel. J Prosthet Dent 2013;109:22-9.

24. Preis V, Weiser F, Handel G et al: Wear performance of monolithic dental ceramics with different surface treatments. Quintessence Int 2013;44;393-405.

25. Stawarczyk B, Özcan M, Schmutz F et al: Two-body wear of monolithic, veneered and glazed zirconia and their corresponding enamel antagonists. Acta Odontol Scand 2013;71:102-12.

26. Vieira AC, Oliveira MC, Lima EM et al: Evaluation of the surface roughness in dental ceramics submitted to different finishing and polishing methods. J Ind Prosthodont Soc 2013;13;290-5.

27. Strom G, Frederiksson M, Stenius P et al: Kinetics of steady-state wetting. J Colloid Interface Sci 1990;134:107-15.

28. Eichhold WA, Brown DT: Wear rates of various artificial tooth materials: a literature review. Compend Contin Educ Dent 1996;17:1074-6, 1078.

29. Kosmac T, Oblak C, Jevnikar P et al: The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. Dent Mater 1999;15:426-433.

30. Guazzato M, Quach L, Albakry M et al: Influence of surface and heat treatments on the flexural strength of Y-TZP dental ceramic. J Dent 2005;33:9-18.

31. Chevalier J: What future for zirconia as a biomaterial? Biomaterials 2006;27:535-543.

32. Gupta TK: Strengthening by surface damage in metastable tetragonal zirconia. J Am Ceram Soc 1980;63:117.

33. Green DJ: A technique for introducing surface compression into zirconia ceramics. J Am Ceram Soc 1983;66:c178-c179.

34. Swain MV, Hannink RH: Metastablility of the martensitic transformation in a 12 mol% ceriazirconia alloy: II, grinding studies. J Am Ceram Soc 1989;72:1358-1364.

35. Xu HH, Jahanmir S, Ives LK: Effect of grinding on strength of tetragonal zirconia and zirconia-toughened alumina. Mach Sci Technol 1997;1:49-66.

36. Michida S, Kimpara ET, Santos C et al: Effect of air-abrasion and polishing regimens on flexural strength, Weibull modulus and phase transformation of Yttrium-stabilized policrystaline tetragonal zirconia. J Appl Biomater Function Mater 2014 (Epub).

Captions to the tables and legends:

Tables:

Table 1. Summary of the available literature on the polishing systems on ceramics including monolithic zirconia in relation to antagonist wear, adapted after Passos et al.[14]

Table 2. Brands of grinding and polishing instruments, their manufacturers, recommended procedures, chemical composition, mechanical and physical properties and their clinical function according to the manufacturers.

Table 3. Experimental conditions for grinding and polishing steps applied on monolithic zirconia specimens. For group abbreviations see Table 1.

Table 4. Significant differences between polishing systems studied on monolithic zirconia for the parameters ΔW, ΔV, ΔVH, ΔRa, ΔSW (ANOVA, Scheffé).

Table 5. Significant differences between baseline and final polishing steps for each polishing system for the parameters of ΔW, ΔRa, ΔSW (Wilcoxon).

Table 6. Significant differences between baseline and final polishing steps for each polishing system for the digital microscope parameters of ΔV, ΔVH (Wilcoxon).

Table 7. Correlation coefficients between ΔW vs. ΔV and ΔRa vs. ΔVH obtained from digital microscope (x200), when polishing instruments are applied under the experimental conditions presented in Table 2. For group abbreviations see Table 1.

Legends:

Fig. 1 Flow chart of the experimental procedures.

Figs. 2a-b a) Custom made grinding and polishing device where force and rpm could be controlled, **b)** monolithic zirconia specimen in the holder of the device in relation to the bur.

Figs. 3a-f Grinding and polishing instruments used for the experiments in sequence **a)** GB, **b)** BG, **c)** CG, **d)** EV, **e)** SL from both views, and **f)** DB. Note that each polishing system has different number of polishing steps from coarse to fine. For group abbreviations see Table 1.

Figs. 4a-f Digital microscope images (x200) of **a)** GB, **b)** BG, **c)** CG, **d)** EV, **e)** SL and **f)** DB. Note that none of the polishing regimens could eliminate surface grooves completely, presenting different levels of peaks and valleys. EV (*) even produced deeper irregularities and SL produced gradient traces (black arrow). For group abbreviations see Table 1.

Figs. 5a-e a) Photos of the grinding bur (GB) and SEM images of the same bur **b)** x40, **c)** x2000 before and **d)** x40, **e)** x2000 after use. Note the smear layer accompanied with diamond loss after 5 times of use.

Figs. 6a-e a,f,k) Photos of BG consisting 3 polishers used in sequence and SEM images of these polishers **b,g,l)** x40, **c,h,m)** x2000 before and **d,i,n)** x40, **e,j,o)** x2000 after use. Note the smear layer accompanied with diamond loss after 5 times of use. Note the loss of silicon carbide particles after 5 times of use.

Figs. 7a-e a,f,k) Photos of CG consisting 3 polishers used in sequence and SEM images of these polishers **b,g,l)** x40, **c,h,m)** x2000 before and **d,i,n)** x40, **e,j,o)** x2000 after use. Note the smear layer accompanied with detachment of diamonds from the surface after 5 times of use.

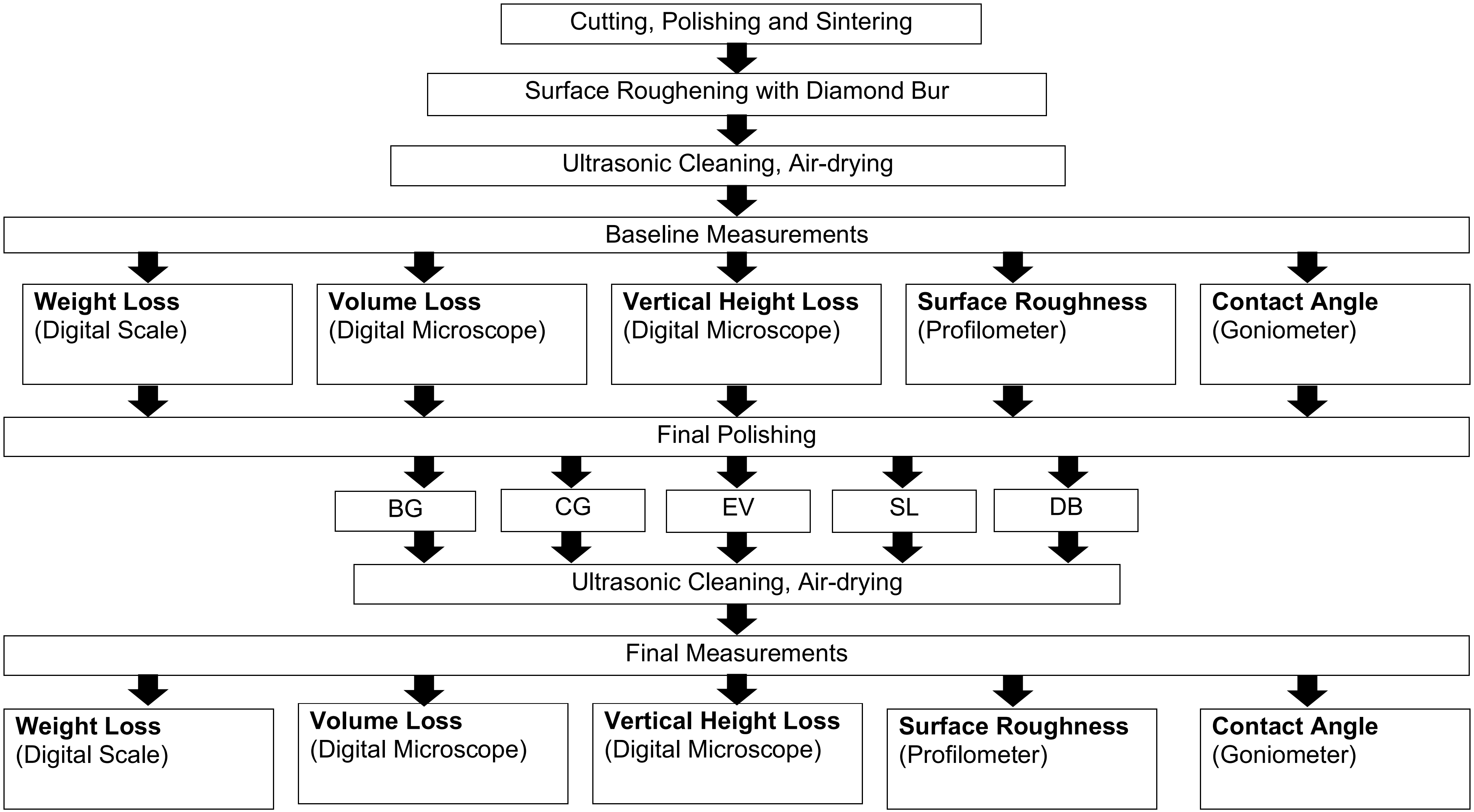
Figs. 8a-e a,f,k) Photos of EV consisting 3 polishers used in sequence and SEM images of these polishers **b,g,l)** x40, **c,h,m)** x2000 before and **d,i,n)** x40, **e,j,o)** x2000 after use. Note the smear layer accompanied with gradual loss of diamonds from the surface after 5 times of use in **a** and **f**, and no diamonds in **k** before use.

Figs. 9a-e a,f,k,p) Photos of SL consisting 4 polishing disks used in sequence and SEM images of these disks **b,g,l, q)** x40, **c,h,m,r)** x2000 before and **d,i,n,s)** x40, **e,j,o,t)** x2000 after use. Note the smear layer accompanied with gradual loss of diamonds from the surface after 5 times of use in a and f, and no diamonds in k before use.

Figs. 10a-e a) Photos of DB and SEM images of the same bur **b)** x40, **c)** x2000 before and **d)** x40, **e)** x2000 after use. Note the smear layer accompanied with diamond loss after 5 times of use.

Figs. 11a-f Photos and elemental mapping (C, O, Zi, Si) of **a)** GB, **b)** BG, **c)** CG, **d)** EV, **e)** SL, **f)** DB after 10 s of use.

Figures:



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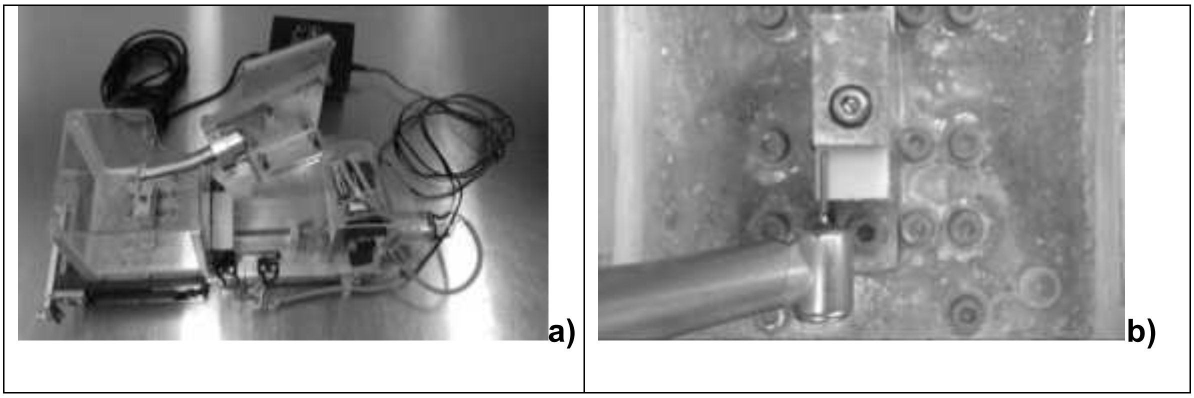

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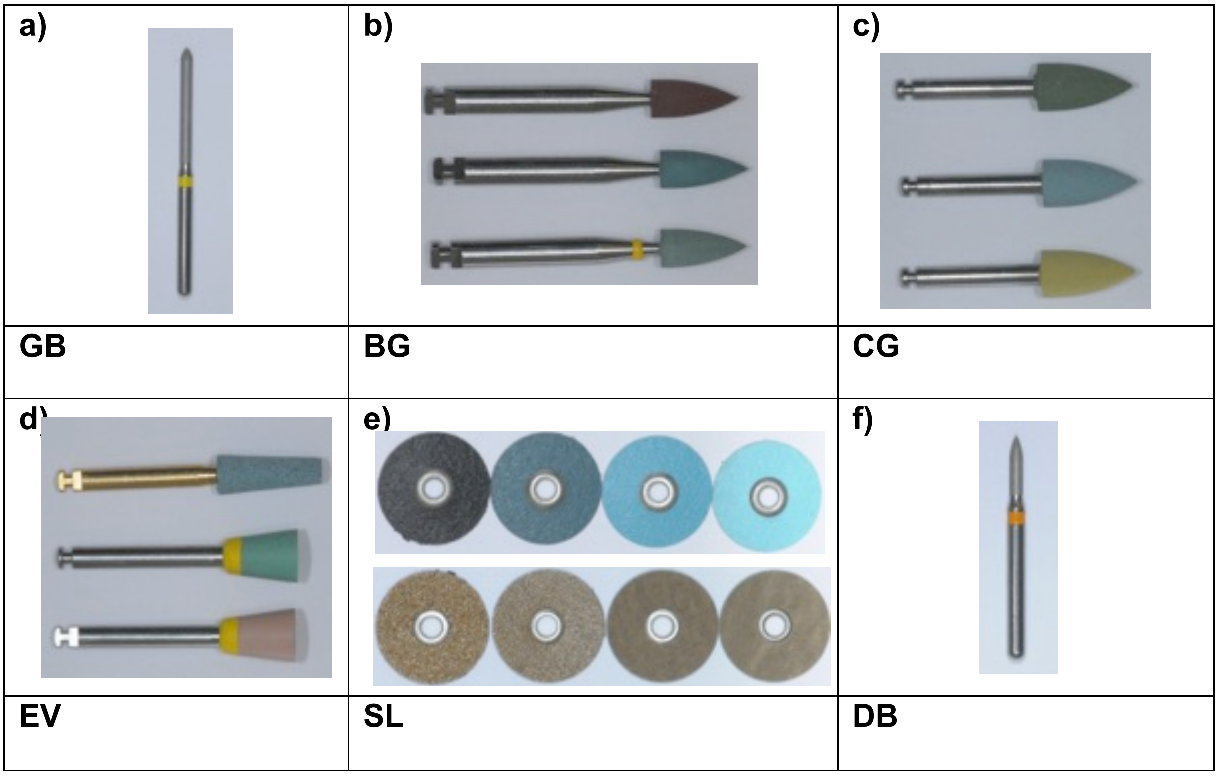

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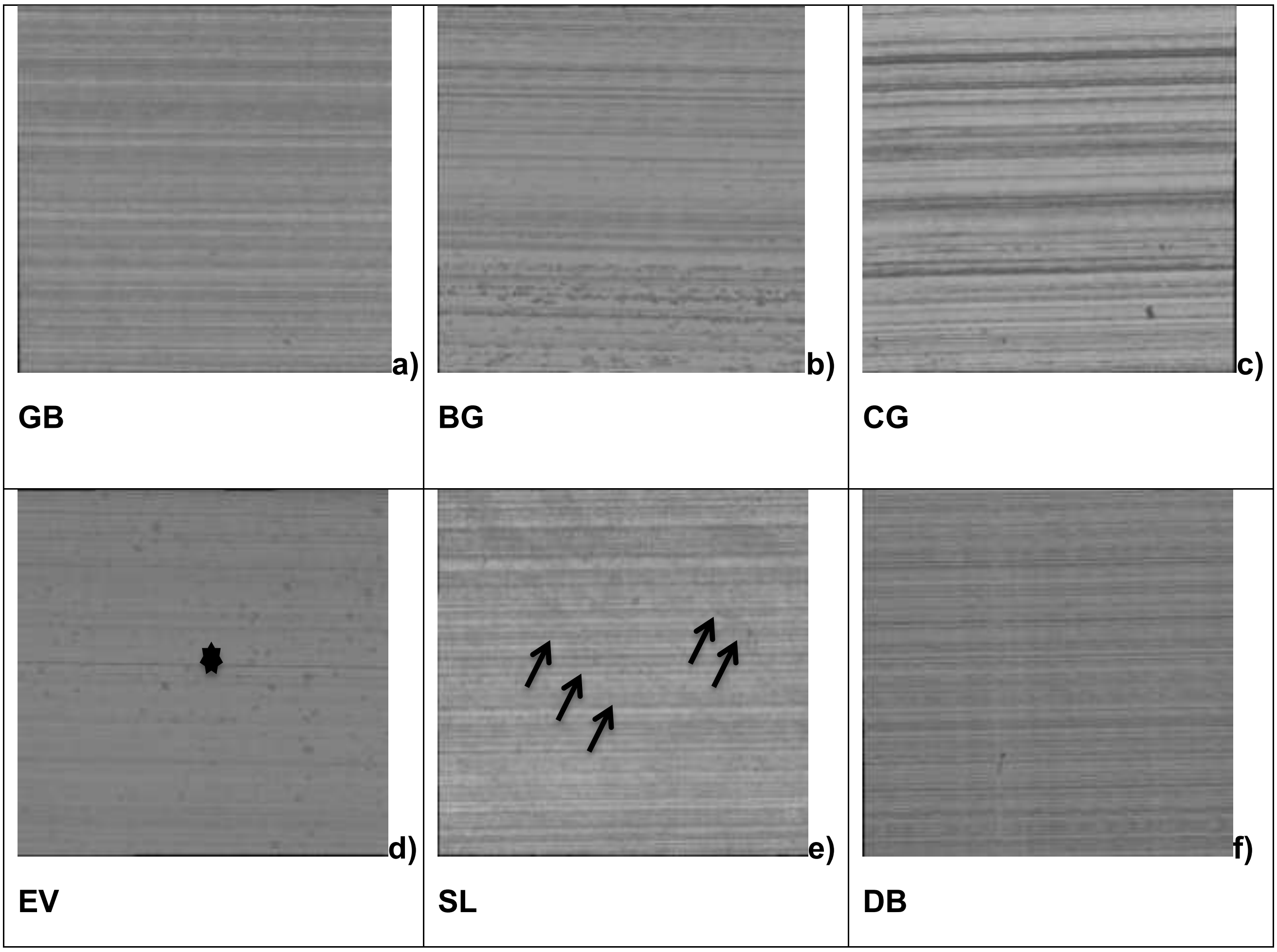

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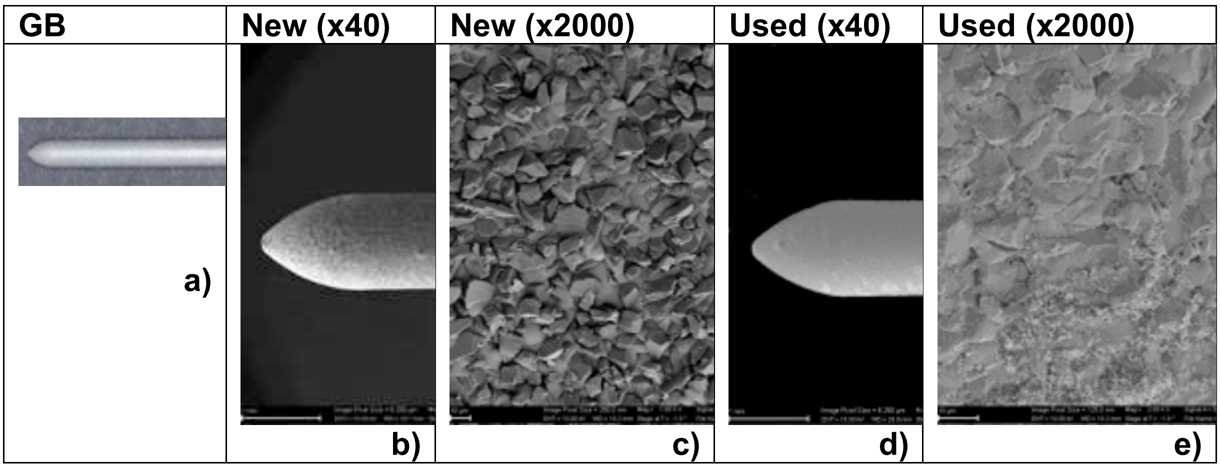

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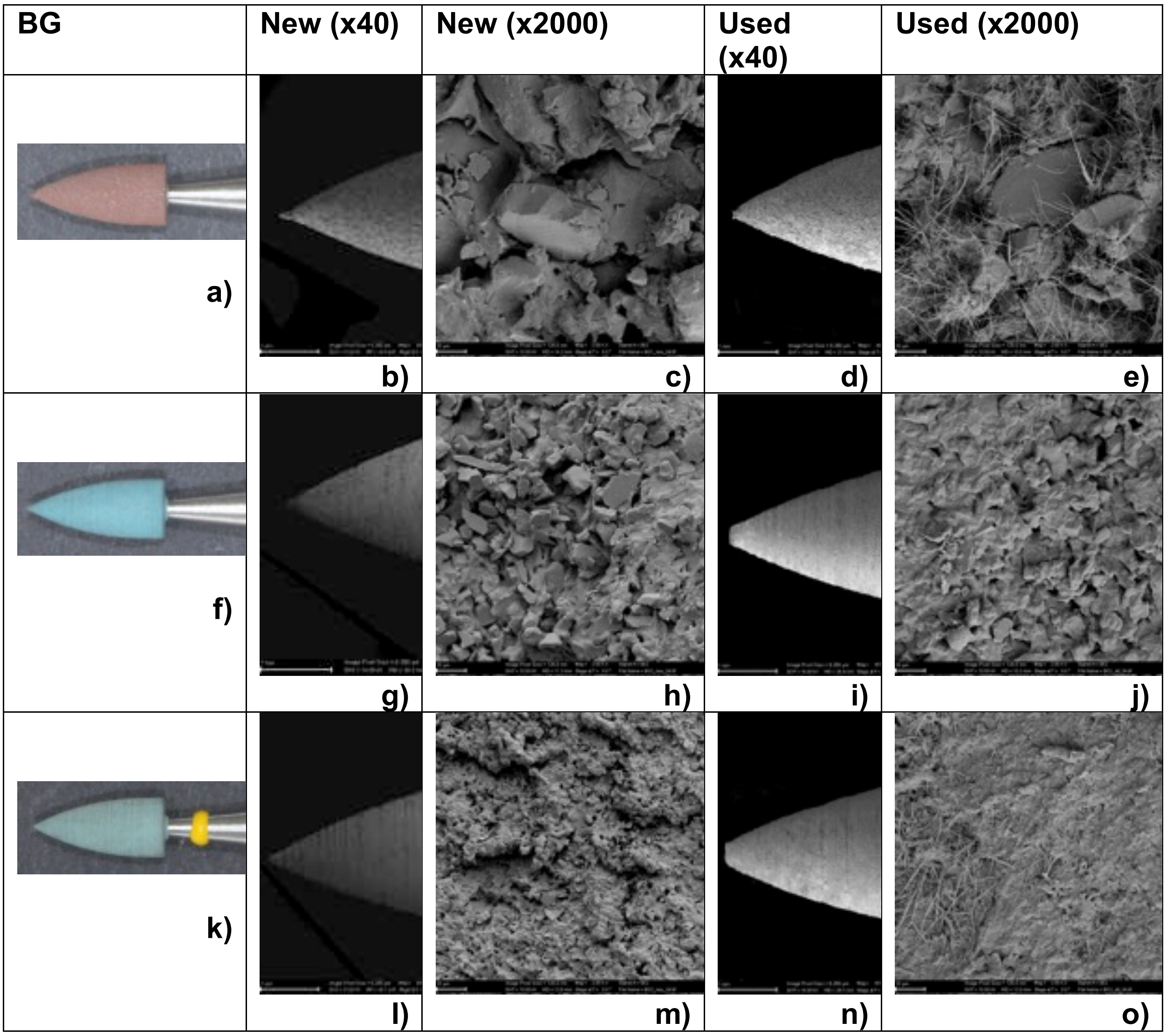

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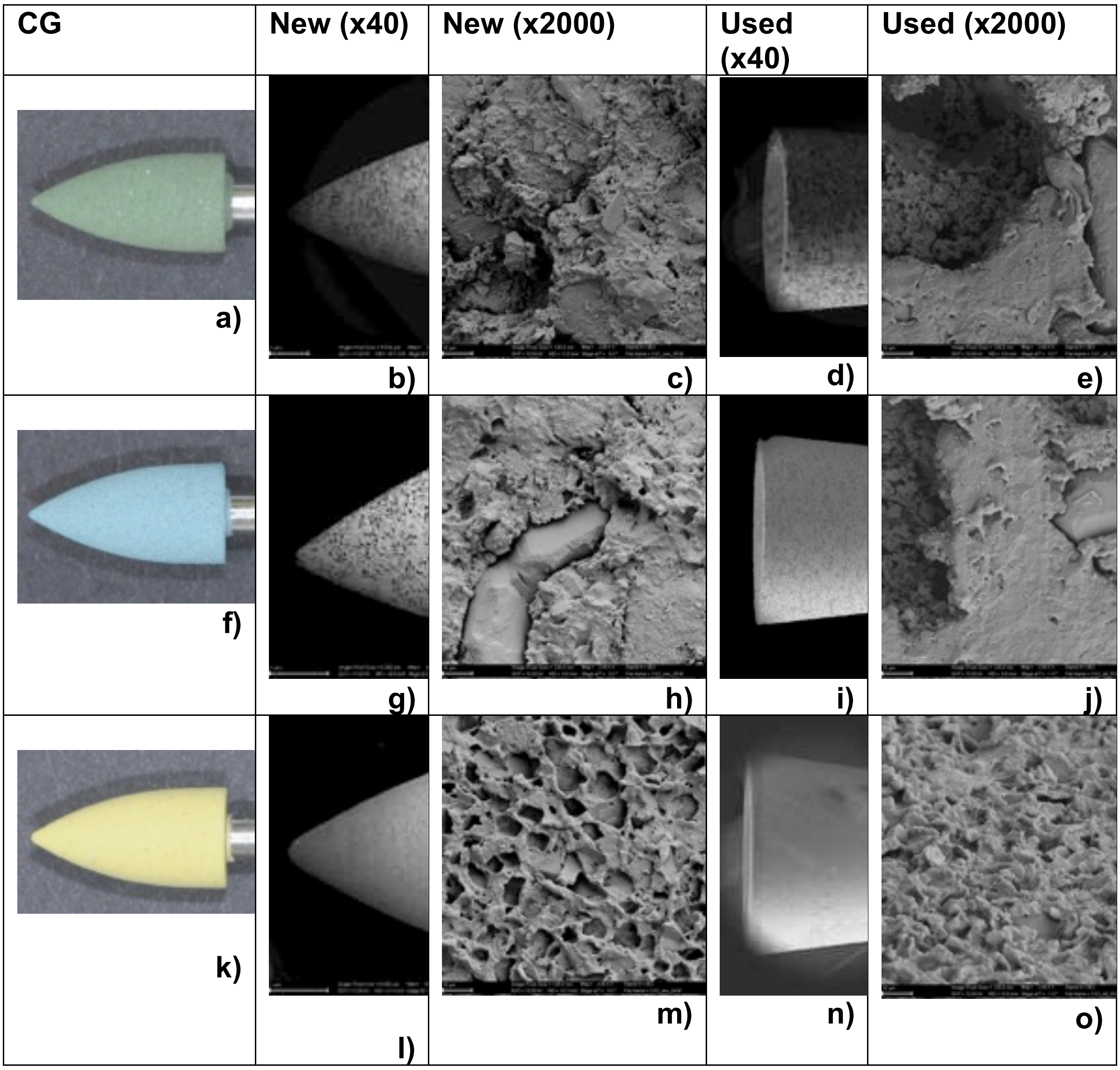

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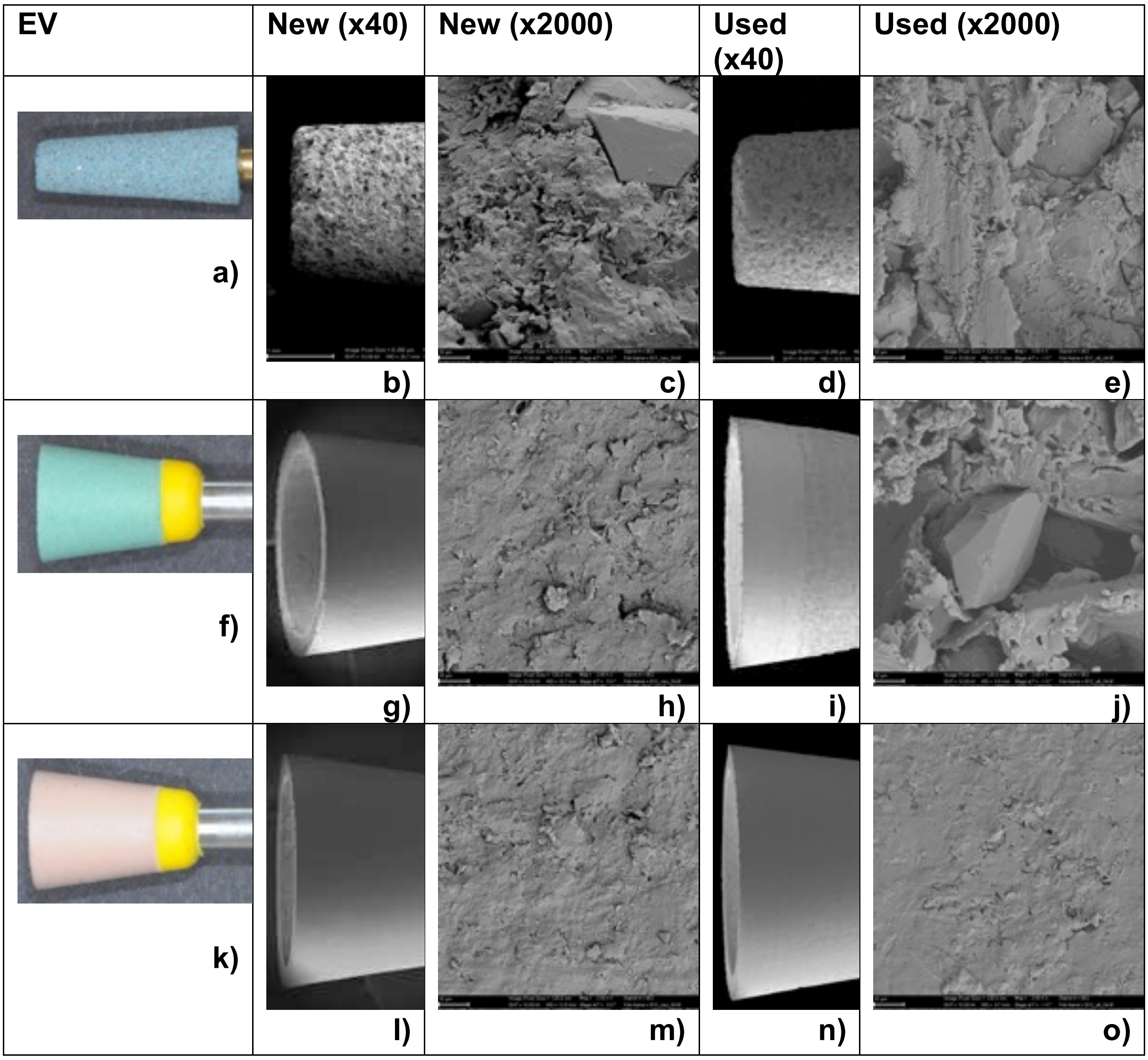
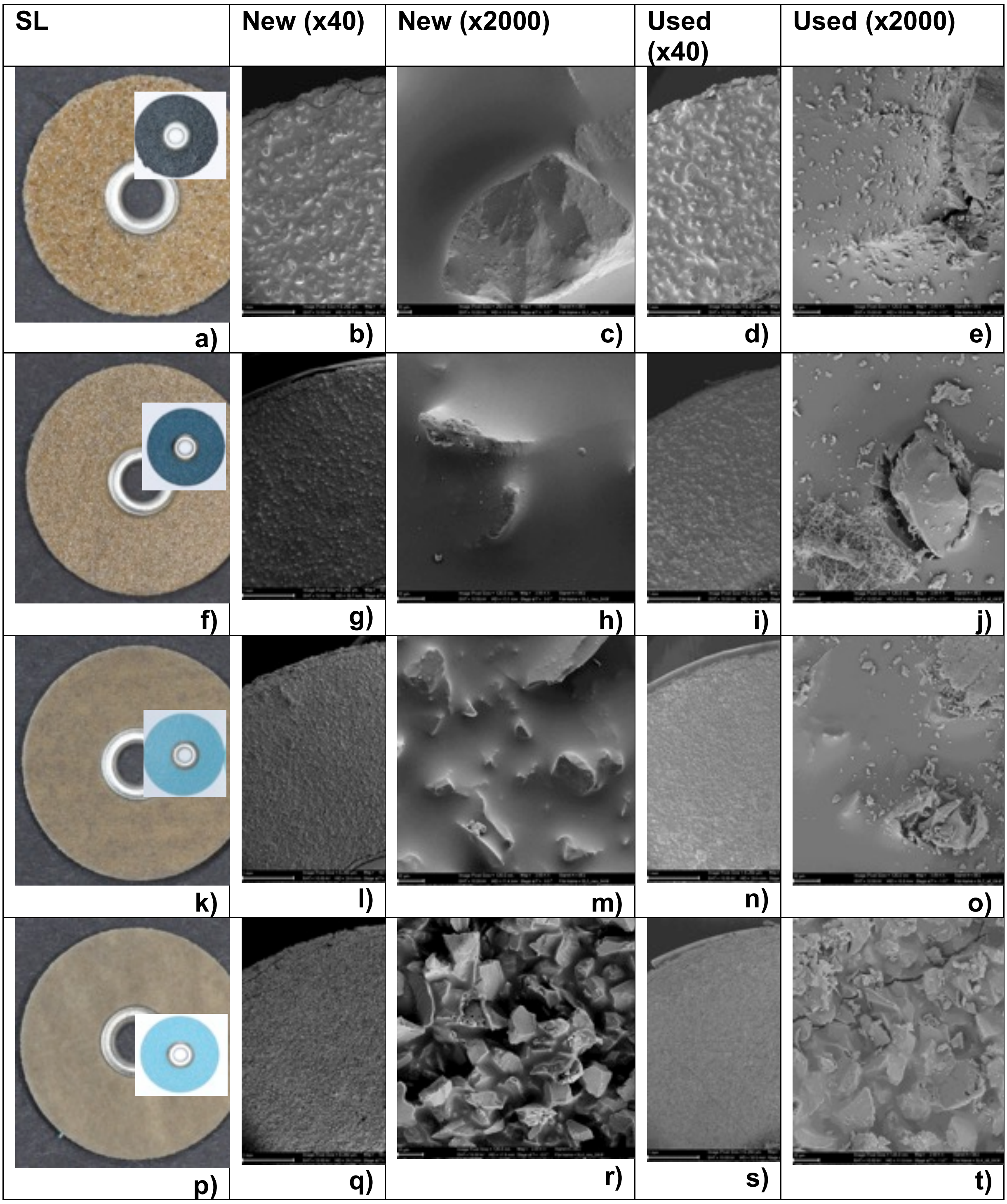


Figs. 8a-e a,f,k) Photos of EV consisting 3 polishers used in sequence and SEM images of these polishers **b,g,l)** x40, **c,h,m)** x2000 before and **d,i,n)** x40, **e,j,o)** x2000 after use. Note the smear layer accompanied with gradual loss of diamonds from the surface after 5 times of use in **a** and **f**, and no diamonds in **k** before use.



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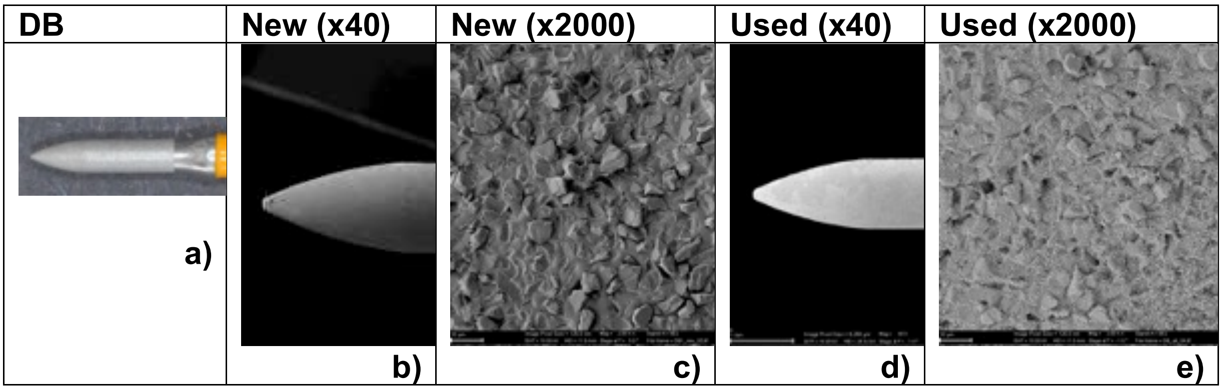

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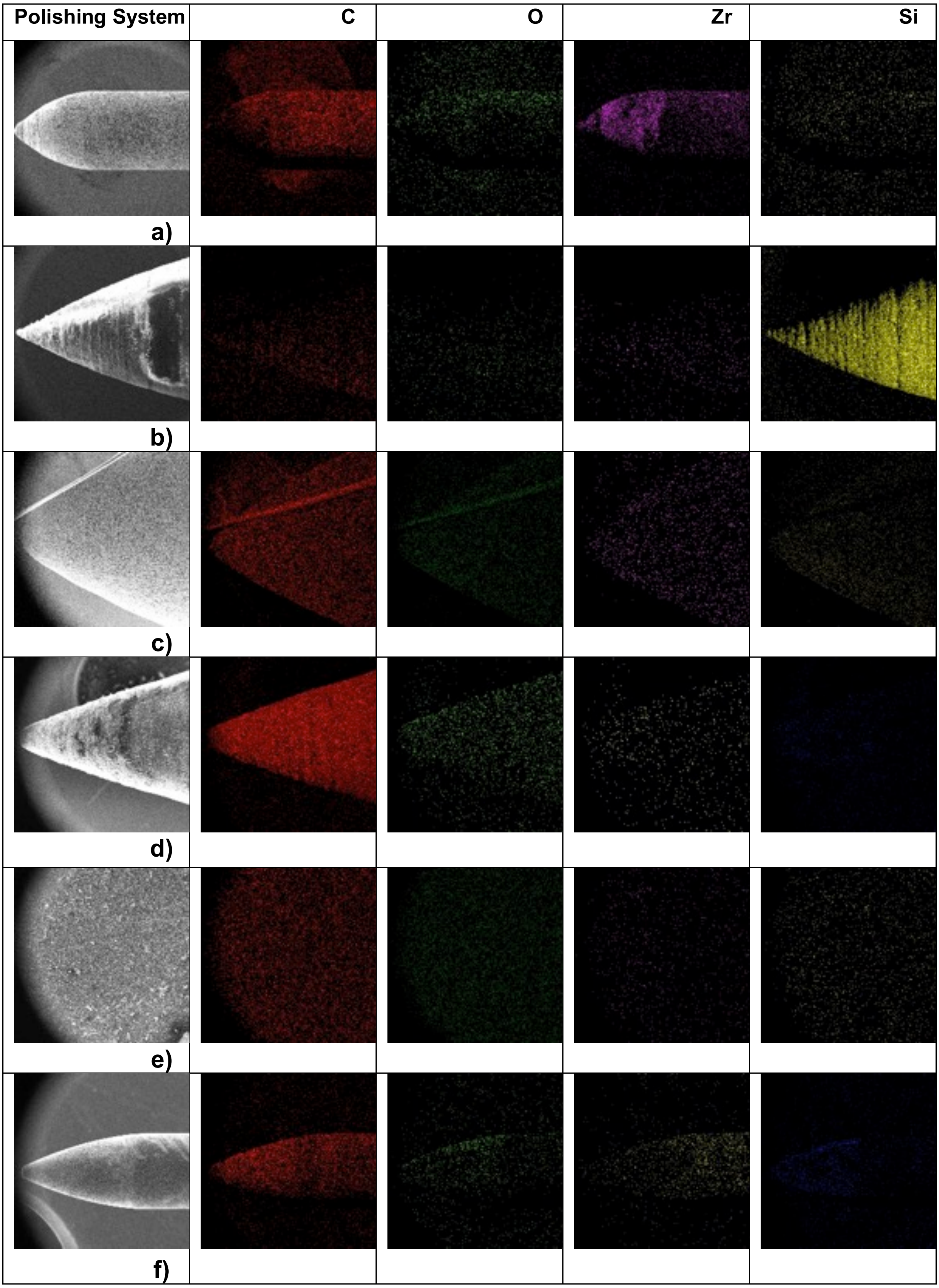

Figs. 11a-f Photos and elemental mapping (C, O, Zi, Si) of **a)** GB, **b)** BG, **c)** CG, **d)** EV, **e)** SL, **f)** DB after 10 s of use.

Tables:

Experimental conditions	Janyavula et al.[16]	Stawarczyk et al.[18]	Jung et al.[14]	Mitov et al.[15]	Flury et al.[13]	Preis et al.[17]	Vieira et al.[19]
Fatigue device	Dual-axis Simulator (Alabama), vertical and horizontal movement	Controlled masticator comprised occlusal loading (Zurich)	Dual-axis Simulator (CS 4.8), vertical and horizontal movement	Dual-axis simulator (Ivoclar), vertical and horizontal movement	-	Chewing simulator, two-body wear	-
Wear parameters	10 N, 0.33 Hz, 2 mm sliding, 200.000,400.000 cycles, 33% glycerine and 66% distilled water	49 N, 1.7 Hz, 120.000, 240.000, 640.000 and 1.200.000 cycles, water 5°/50°C	5 kg, 0.8 Hz, 0.3 mm sliding, 240.000 cycles, water 5°/55°C	5 kg, 1.6 Hz, 0.7 mm sliding, 120.000 cycles, demineralized water	-	50 N, 1.6 Hz, 1 mm sliding, 120.000 cycles, water 5°/55°C	-
Wear evaluation	3D-Profilometer: Records volume loss by overlapping the 3D scans before and after the wear test	3D-Profilometer: Records the vertical loss by overlapping the 3D scans before and after the wear test	3D-Profilometer: Records volume loss by overlapping the 3D scans before and after the wear test	3D laser scanner: Records the maximal vertical loss and the mean vertical loss	Profilometry: Records average surface roughness (Ra) and arithmetic mean height of the surface profile (Rz)	3D Profilometry: Records Ra, vertical loss. Light microscope: records wear of steatite antagonist	Rugosimeter: Records roughness Ra
Number of specimens	8	6	20	16	240	8	144
Enamel antagonist	Mandibular molar mesiobuccal cusps	Maxillary molar mesiobuccal cusps	Maxillary premolars buccal cusps	First or second maxillary molar cusps	-	Steatite antagonists	-
Enamel preparation	The tips of the cusps were polished(diamond rotary instrument)	The tips of the cusps were rounded to a spherical shape	1200-grit abrasive paper	Non standardized	-	-	-
Ceramic system	Monolithic zirconia	Zirconia (ZENOTEC Zr Bridge Translucent)	Zirconia (Prettau)	Zirconia (Everest ZH)	VITABLOCS Mark II, IPS Empress CAD	Zirconia (Experimental translucent, shaded zirconia) lithium disilicate	Glass ceramic (VITA Zahnfabrik VITAVM7, 9, 13)

Specimen shape	Flat	Flat	Cuboidal	Flat	Flat	Flat	Flat
Experimental groups	Control (veneering porcelain and enamel),polished zirconia, glazed zirconia, polished and reglazed	Control (monolithic base alloy), veneered zirconia, glazed zirconia with a glaze ceramic, glazed zirconia with a glaze spray, manually polished zirconia, mechanically polished zirconia	Polished feldspar, polished zirconia,polished zirconia with glazing	Control (polished leucite-reinforced glass ceramic), four different finishing procedures for zirconia: polished, fine-grit diamond, coarse-grit diamond, glazed	Control (Glazed specimens), five different polishing methods (EVE Diacera, JOTA, Optrafine, Sof-Lex, Brownie/Greenie/ Occlubrush)	Polished (BruxZir Set), polished-ground, polished-ground-repolished, glazed	Control (glaze), negative Control (no polishing), Polished: with abrasive rubbers, Brownie/Greenie or Sof-Lex with felt disc and diamond polish paste
Ceramic finishing sequence	Polished, glazed, polished, then reglazed	Glazed with a glaze ceramic, glazed with a glaze spray, manually polished, mechanically polished	Polished, polished with glazing	Polished, fine-grit diamond, coarse-grit diamond, glazed	Ground mechanically with silicon carbide papers, polished	Ground with diamond bur manually	Simulated occlusal wear with diamond point
Glaze conditions	FCZ glaze	Glaze ceramic: Glaze Zirox with Stain Liquid Glaze spray: ZENOStar Magic	Glazing of Zirkonzahn Prettau	Vita Akzent VM9	VITABLOCS Mark II and IPS Empress CAD	Experimental translucent, shaded zirconia and lithium disilicate	VITA Zahnfabrik VITAVM7, 9, 13
Wear results	E: polished then reglazed =glazed > polished. No difference for the different cycles M: polished then reglazed =glazed > polished	E: glazed with a glaze ceramic > glazed with a glaze spray = polished M: glazed >polished	E: coarse-grit diamond > polished. No difference among polished, fine-grit diamond and glazed. M: no measurable wear observed. Except for the glazed group	E: glazed > polished M: not reported.	E: glazed > polished, Sof-Lex exhibited smoothest surfaces using VITA and IPS	Glaze> polished, ground and repolished zirconia	Glaze < polished; Shofu<Sof-Lex,Edenta

Enamel antagonist wear- vertical substance loss (µm), volume loss (mm^3), wear scars widths (µm)	Polished + 200.000 cycles: 0.11 (0.04) mm^3. Glazed +200.000 cycles: 0.87 (0.21) mm^3. Polished then reglazed + 200.000 cycles: 0.59 (0.1) mm^3 Polished + 400.000 cycles: 0.21 (0.05) mm^3 Glazed +400.000 cycles:1.18 (0.2) mm^3 Polished then reglazed +400.000 cycles: 0.88 (0.12) mm^3	Glazed with a glaze ceramic: 51.7 to118 *µ*m Glazed with a glaze spray: 24.5 to 62.2 *µ*m Manually polished: 14.3 to 27.3 *µ*m Mechanically polished: 14.7 to 28 *µ*m	Polished: 171.74 (121.68) *µ*m	Glazed: 0.078 (0.063) mm^3 Polished: 0.031 (0.033) mm^3	-	Enamel vs steatite: 274.14 *µ*m Vertical loss Lithiumdisilicate > zirconia Zirconia: 0.86 translucent, repolished, 1.57 shaded polish-ground, 1.79 lithiumdisilicate repolished	-
SEM analysis	Yes	Yes	No	Yes	Yes	Yes	No

Table 1 Summary of the available literature on the polishing systems on ceramics including monolithic zirconia in relation to antagonist wear, adapted after Passos et al.[15]

Instrument (Abbreviations)	Manufacturer	Recommended procedure by the manufacturer			Chemical composition	Mechanical and physical properties	Clinical function
		Rotation per minute (Rpm)	Water (50 ml/min)	Load			
Grinding bur (FG 5410L/6)	Intensiv, Montagnola, Switzerland	55’000-160’000	Yes	10 g	Diamond particles imbedded into binder Matrix material	Grit: 220 µm Diameter: 0.13 mm Length: 12 mm	Finishing
Brownie, Greenie, Super Greenie (BG) (FG 0413, FG 0414, 414B)	Shofu, Ratingen, Germany	5’000-7’000	Yes	1-2 N	Silicon carbide polishers	Diameter: 0.30 mm	Prepolish, polish and superpolish
Ceragloss (335 RA, 3035 RA, 30035 RA)	Edenta, St. Gallen, Switzerland	10’000-12’000	Yes		Diamond impregnated ceramic polisher kit	Length: 10 mm	Finishing, polishing and high-lustre polishing
EVE Kit (EV) (DYP-W13m[1], W16DCmf[2], W16DC[2]	EVE,Pforzheim, Germany	1) 8’000-12’000 2) 7’000-10’000	Yes		Synthetically bonded grinder interspersed with diamond	1) 4 mm x 10 mm 2) 6 mm x 7.5 mm	Smoothing, prepolish, high-gloss polish
Soflex Finishing and Polishing System Kit (SL)	3M ESPE, Paul, MN, USA	10’000 30’000	No		Urethane coated paper aluminium oxide grits	13 mm discs	Finishing, polishing
Diamond Bur (DB) (FG9205/6)	Intensiv	75’000	Yes	10 g	Diamond particles embedded into binder matrix material	8 µm	Polishing

Table 2 Brands of grinding and polishing instruments, their manufacturers, recommended procedures, chemical composition, mechanical and physical properties and their clinical function according to the manufacturers.

Experimental Conditions				
	Rpm	**Time (s)**	**Pressure (N)**	**Rinse (50 ml/min)**
Grinding Step				
Grinding bur	160'000	10	0.75	Yes
Polishing Steps				
BG (3 Steps)	1st, 2nd, 3rd 5'000	30	0.75	Yes
CG (3 Steps)	10'000	30	0.75	Yes
EV (3 Steps)	1st 7'000 2nd 3rd 10'000	30	0.75	Yes
SL (4 Steps)	1st, 2nd, 3rd 4th 10'000	40	0.75	
DB	75'000	10	0.75	Yes

Table 3 Experimental conditions for grinding and polishing steps applied on monolithic zirconia specimens. For group abbreviations see Table 1.

Polishing System		ΔW	ΔV	ΔVH	ΔRa	ΔSW
BG	**CG**	0.999	0.998	0.998	0.929	0.530
	EV	0.000*	0.000*	0.000*	0.000*	0.243
	SL	0.932	0.887	0.998	1.000	0.671
	DB	0.031*	0.998	0.530	0.989	1.000
CG	**EV**	0.000*	0.001*	0.000*	0.000*	0.986
	SL	0.979	0.744	0.975	0.963	0.999
	DB	0.017*	1.000	0.714	0.704	0.644
EV	**SL**	0.000*	0.000*	0.000*	0.000*	0.948
	DB	0.000*	0.001*	0.002*	0.000*	0.330
SL	**DB**	0.003*	0.745	0.344	0.973	0.777

Table 4 *P* values for significant differences between polishing systems studied on monolithic zirconia for the parameters ΔW, ΔV, ΔVH, ΔRa, ΔSW (ANOVA, Scheffé, *P*<0.05). *Indicates significant differences between polishing systems considering each parameter.

Polishing System	*P* values	$W_{Baseline}$	$W_{final\ polish}$	ΔW (g)	*P* values	$Ra_{Baseline}$	$Ra_{final\ polish}$	ΔRa (µm)	*P* values	$SW_{Baseline}$	$SW_{final\ polish}$	ΔSW (°)
BG	0.011*	1.60	1.60	0.002	0.005*	0.29	0.27	-0.02	0.203	57.19	59.98	-2.79
CG	0.005*	1.61	1.61	0.002	0.047*	0.26	0.40	0.14	0.285	59.68	57.42	2.26
EV	0.005*	1.67	1.64	0.03	0.005*	0.25	1.11	0.86	0.022*	59.32	55.38	3.93
SL	0.005*	1.65	1.64	0.0003	0.575	0.29	0.29	-0.01	0.575	61.91	60.37	1.54
DB	0.005*	1.67	1.66	0.01	0.074	0.28	0.13	-0.14	0.445	55.54	57.75	-2.21

Table 5 Significant differences between baseline and final polishing steps for each polishing system for the parameters of ∆W, ∆Ra, ∆SW (Wilcoxon, $P<0.05$). *Indicates significant effect of polishing system on weight (∆W), surface roughness (∆Ra) and surface wettability (∆SW) parameters.

Polishing System	***P* values**	$V_{Baseline}$	$V_{final\ polish}$	**∆V (μm³)**	***P* values**	$VH_{Baseline}$	$VH_{final\ polish}$	**∆VH (μm)**
BG	0.005*	3853×10^5	2954×10^5	900×10^5	0.013*	83.142	68.175	14.976
CG	0.009*	2724×10^5	2039×10^5	685×10^5	0.005*	59.412	48.149	11.263
EV	0.013*	5712×10^5	8171×10^5	2459×10^5	0.005*	118.47	173.66	-55.19
SL	0.005*	5244×10^5	3662×10^5	1582×10^5	0.203	112.541	93.63	18.911
DB	0.022*	3329×10^5	2642×10^5	687×10^5	0.799	73.025	77.824	-4.799

Table 6 Significant differences between baseline and final polishing steps for each polishing system for the parameters of ∆V, ∆VH (Wilcoxon, $P<0.05$). *Indicates significant effect of polishing system on weight (∆V) and vertical height loss (∆VH).